

# All-optical switching effect based on azodye-doped polymer thin films

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A simple all-optical switch based on photoinduced birefringence effect is demonstrated in azo dye (DR1) doped polymer (PMMA) thin films. The all-optical switching effect has been studied at different control beam power and different temperatures of the sample. With a control power of 30.7 mW and at 56 °C, the response time of the switching is less than 5 ms, and the depth of the modulation reaches 80%.

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Nonlinear optical (NLO) polymers offer great promise for use in optical memories, switches, modulators, and other opto-electronic devices due to their large linear electro-optic coefficients, low dielectric constants, flexibility in fabrication, and the processing techniques which are compatible with integrated circuit technology<sup>[1]</sup>. Recently, all-optical switches based on the photoinduced refractive index changes in the photochromic dye-doped polymer materials have attracted much interest. Based on Mach-Zehnder optical switches, Ebisawa *et al.*<sup>[2]</sup> reported their switch using SiO<sub>2</sub> and a photochromic polymer. The response times of 1.55 μm laser light were 95 s at 313 nm (5 mW/cm<sup>2</sup>) and 50 s at 500 nm (10 μW/cm<sup>2</sup>). Rodriguez *et al.*<sup>[3]</sup> used 514 nm (20 mW/cm<sup>2</sup>) light to pump the PMMA-DR1 polymer and the response time of 1.064 μm light was 20 s. Kang *et al.*<sup>[4]</sup> pumped their dye-doped polymer waveguide with 514 nm (7 mW/cm<sup>2</sup>) and 365 nm (0.4 mW/cm<sup>2</sup>), and the response time of 1.55 μm light is large than 1 s. Okamoto *et al.*<sup>[5]</sup> reported an optical photoaddressed spatial light modulator (SLM) using a dye-doped polymer (PVA) film in a surface plasmon resonance (SPR) configuration. The rise and fall times of 488 nm (6 W/cm<sup>2</sup>) Ar<sup>+</sup> laser were about 10 and 2 s, respectively. Yacoubian and Aye<sup>[6]</sup> proposed Fabry-Perot (FP) resonance shifting in attenuated total reflection (ATR) geometry using azo-dye polymers. Pumping with Ar<sup>+</sup> laser (514 nm, 10 mW/cm<sup>2</sup>), the response time of He-Ne laser light was 50 – 200 ms. The control light power of these systems above are low, but the response speed is still relatively slow. Nagamura *et al.*<sup>[7]</sup> reported optical modulation of reflected intensity based on photoinduced imaginary part change of refractive index of CuPcS-doped PVA thin films in ATR geometry. Pumping with 682 nm (5 ns, 0.5 – 2 mJ/pulse, 0.2 cm) light, the rise time and fall time of 514 nm probing light were 0.12 and 0.92 ms, respectively. Sasaki *et al.*<sup>[8]</sup> proposed their all optical switch using SPR configuration. They used light at 355 nm (8 ns, 1 – 2.5 mJ/pulse) and 600 nm (8 ns, 6 mJ/pulse) as switch on and off signal to pump the photochromic polymer, respectively. The rise time of 543 nm light was about 20 ns. Though these switches respond faster, the pumping light intensity is quite higher.

In this letter, we report a simple all-optical switch based on photoinduced birefringence effect of poly(methyl-methacrylate) (PMMA) thin film which is doped with azo dye 4-[N-(2-hydroxyethyl)-N-ethyl]amino-4'-nitroazobenzene (DR1). The concentration of DR1 is 2.5wt%. The polymer thin film with thickness about 300 μm is coated on a glass substrate. Modulated linearly polarized Ar<sup>+</sup> laser beam is used as a control light pumping the sample and a He-Ne laser beam as a signal light to probe the light induced refractive index change. With the control beam power at milliwatt magnitude, we have observed the all-optical switching effect with the response time in several milliseconds and with the depth of the modulation (M) about 80%.

Figure 1 is the transmission spectra of the PMMA-DR1 sample (*T<sub>g</sub>* = 100 °C). The absorption of the sample is much stronger with the wavelength less than 575 nm, and the absorption is much weaker with the wavelength larger than 600 nm. Figure 2 illustrates the geometry used for observing the all-optical switching effect of the polymer sample. The input signal beam from a He-Ne laser (632.8 nm, cw) is linearly polarized by a polarizer. The control beam from argon ion laser (514 nm, cw) is chopped by a mechanical chopper and linearly polarized at 45° with respect to the polarization direction of the signal beam. The signal and control beam are spacial overlapped properly in the sample. After passing through the sample, the signal beam goes through an analyzer (tilted 90° with respect to the initial He-Ne beam polarization). A filter that has an absorption bandwidth centered at 514 nm is placed in front of the detector to remove all the transmitted or scattered light coming from the argon ion laser. The detector includes photomultiplier and a high speed digital oscillograph (Tektronix, TDS-3032 model).

Figure 3 shows the all optical switching effect of the sample at room temperature with the control beam power at 23.2 mW. It is clear that when the control beam is turned on, the intensity of the signal beam detected after the analyzer increases with a rising time about several milliseconds. When the control beam is off, the transmitted intensity of signal beam decreases with a falling time about 10 ms. As well known that without the control beam, chromophore (DR1) molecules are randomly

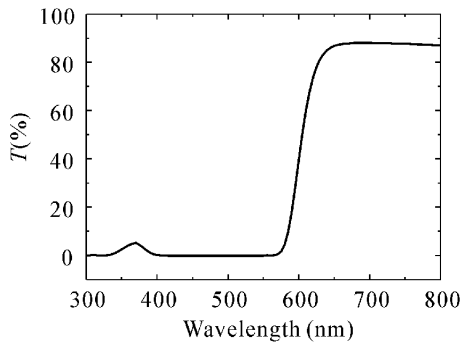


Fig. 1. The transmission spectra of PMMA-DR1 sample.

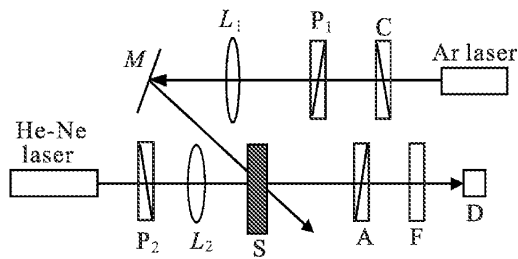


Fig. 2. The setup of the all-optical switch experiment. C: chopper; P<sub>1</sub>, P<sub>2</sub>: polarizers; L<sub>1</sub>, L<sub>2</sub>: lens; M: mirror; S: sample; A: analyzer; F: filter; D: detector.

oriented. The sample is optically isotropic and cannot exhibit any birefringence. In these conditions the He-Ne laser beam does not undergo any polarization modification when passing through the sample and so is completely stopped by the analyzer. While the argon ion laser beam is switching on, the DR1 molecules begin to orientate by trans-to-cis photoisomerizations and then thermally isomerize back to the trans form<sup>[9]</sup>. Chromophores rotate until they are oriented perpendicularly to the direction of the control beam polarization. In such a position, the control light cannot stimulate the electronic transition any longer. When chromophores are aligned the sample exhibits birefringence. The polarization of He-Ne beam after the polymer film is modified, and its component perpendicular to the analyzer axis can reach the detector.

As a parameter to reflect the quality of the optical switch, we define the depth of modulation of the switching effect  $M$  as

$$M = I_P / I_m, \tag{1}$$

where  $I_P$  is the peak-valley difference of the time dependences of transmitted intensity curve of the signal beam and  $I_m$  is the peak value of the curve (see Fig. 3). Figure 4 shows the  $M$  of the sample at a given modulation frequency with the power of control beam and the temperature (by heating) of the sample changing. As the temperature rises, the  $M$  increases at first. After reaching a peak value, the  $M$  begins to decrease. While below the peak-value temperature, one can see that the  $M$  increases with the power of control beam increasing.

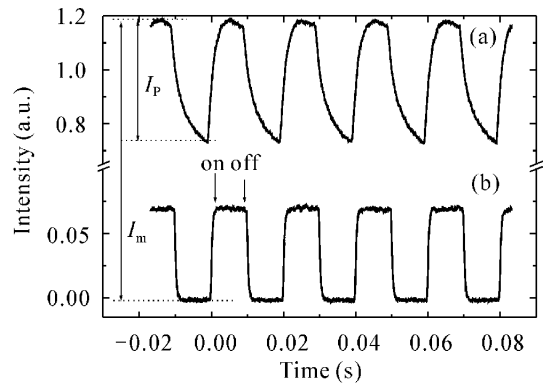


Fig. 3. The all-optical switching effect of the sample at room temperature with control beam power at 23.2 mW. (a): Transmitted intensity of signal beam; (b): modulation of control beam.

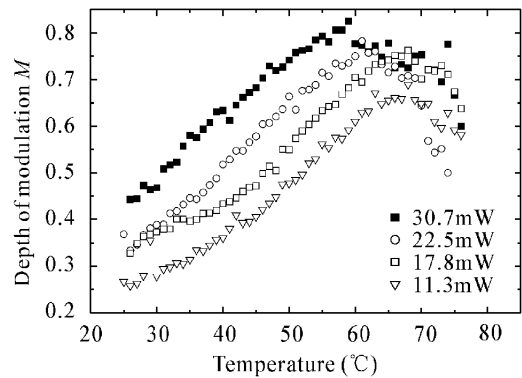


Fig. 4. The depth of modulation  $M$  of the sample at different control beam power and different temperature.

There are two mechanisms in the polymer film which influence the photo-induced birefringence and then determine the optical switching effect. One is the photoisomerization reorientation of the DR1 dye molecules, the other is the rotational diffusion of the DR1 chromophores resulting from thermal agitation. The competition between these two mechanisms can be used to explain the results in Fig. 4 qualitatively. The thermal agitation comes from the heating of the sample and the thermal effect of the control beam illumination owing to the strong absorption of the sample. As the control beam power increases, the temperature of the sample will increase (to some extent, it is equivalent to increase the temperature of the sample by heating at a relative low control beam power). Higher control beam power or higher sample temperature makes the trans-cis photoisomerization cycles faster and makes the chromophores molecules orientate more easily with the control beam radiation, which leads to the sample responding quicker. At the same time, at higher temperature, the chromophores are easier to return to their initial random orientation when the control beam is off, which decreases the background of the transmitted intensity of the signal beam. So with the increase of the control beam power or the temperature of sample, the response of switching effect of the sample becomes quicker, and the depth of modulation  $M$  becomes larger (see Fig. 4). However, as the temperature approaching the

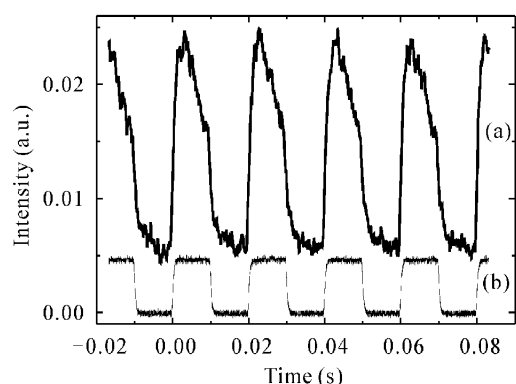


Fig. 5. The all-optical switching effect of the sample at 56 °C and control beam power 30.7 mW. (a): Transmitted intensity of signal beam; (b): modulation of control beam.

$T_g$ , the thermal motions of the DR1 chromophores and the segments of the polymer main chain increase. So, at higher temperature the thermal disturbance which enhances the rotational diffusion disorders the alignment of DR1 molecules becomes stronger and then weakens the photo-induced birefringence. Inversely, this makes  $M$  decrease. As a result, the competition between these two mechanisms will make  $M$  non-monotone (see Fig. 4). On the other hand, it has been known that the isomerization of azo molecules needs the free volume<sup>[10,11]</sup>. Some of the molecules ("free" molecules) in large sizes of the free volume can keep their orientation when turn off the control beam<sup>[12]</sup>. Moreover, at the chopping frequency of 50 Hz, some of the molecules ("trapped" molecules)<sup>[12]</sup>, which can restore their original orientations when the control beam is off, have not enough time for the relaxation though the temperature is high. This is the reason why the background of the signal beam is difficult to decrease further although the control beam power or the temperature continue to increase. In our experiment, at 56 °C and control power 30.7 mW, we obtain a depth of modulation about 80%, with the rising time and the falling time of the switching effect only in several milliseconds, as shown in Fig. 5.

In summary, we have demonstrated an all-optical

switching effect based on an azo-dye doped polymer film. We study the influence of the control beam power and the temperature of the sample on the switching effect and find that rising the temperature of the film appropriately can increase the switching speed with relative low switching power. In our experiment, the all-optical switch shows the switching speed less than 5 ms and the depth of modulation about 80%.

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